Galaxy Clustering Determined From Numerical Cosmological Simulations.

Adrian Jenkins[1], C.S. Frenk[1], F.R. Pearce[1], P.A. Thomas[2], J.M. Colberg[3], S.D.M. White[3], H.M.P. Couchman [4], J.A. Peacock [5], G. Efstathiou [6] and A.H. Nelson [7]
(The Virgo consortium)
[1] *Dept Physics, South Road, Durham, DH1 3LE, UK*
[2] *CPES, University of Sussex, Falmer, Brighton, BN1 9QH, UK*
[3] *MPA, Garching, Munich D-85740, Germany*
[4] *Dept of Astronomy, University of Western Ontario, London, Ontario, N6A 3K7,Canada*
[5] *Institute for Astronomy, Blackford Hill, Edinburgh, EH9 3HJ, UK*
[6] *Institute of Astronomy, Cambridge, CB2 OHA, UK*
[7] *Dept Physics and Astronomy, UWCC, Cardiff, CF2 3YB, UK*

Abstract

We have simulated the growth of structure in two 100 Mpc boxes for ΛCDM and SCDM universes. These N-body/SPH simulations include a gaseous component which is able to cool radiatively. A fraction of the gas cools into cold dense objects which we identify as galaxies. In this article we give a preliminary analysis of the clustering behaviour of these galaxies concentrating on the ΛCDM model. We find a galaxy correlation function which is very close to a power law and which evolves relatively little with redshift. The pairwise dispersions of the galaxies are significantly lower than the dark matter. The ΛCDM model gives a surprisingly good match to the observational determinations of the galaxy correlation function and pairwise dispersions. This article should be read in conjunction with the article 'Cosmological Galaxy Formation' by Frazer Pearce also in this volume.

1 Introduction

It is impossible at present numerically to model all the physical processes which are involved in galaxy formation. Galaxies, as we see them, are made of baryonic material, and at very least a gaseous component must be included in any modelling. In the hierarchical galaxy formation scenario [5] dissipation by the baryons is also crucial for galaxies to form. However it is not clear that simply including cooling of the gas is a sensible approach numerically as this would appear to lead to catastrophic cooling in the early universe. The continual merging of dark halos leads to some shock reheating of cold gas but it is not obvious that the cooling catastrophy can be averted without help from some other heating mechanism [4]. The most likely heat source is that from star forming regions, particularly supernovae explosions. It seems a reasonable assumption that the energy injected back into the gas from supernovae can act as a negative feedback mechanism and lead to some kind of self-regulation of star formation. This self-regulation is expected to be at its most effective in the early universe when the characteristic depth of the dark matter potential wells was much lower than today.

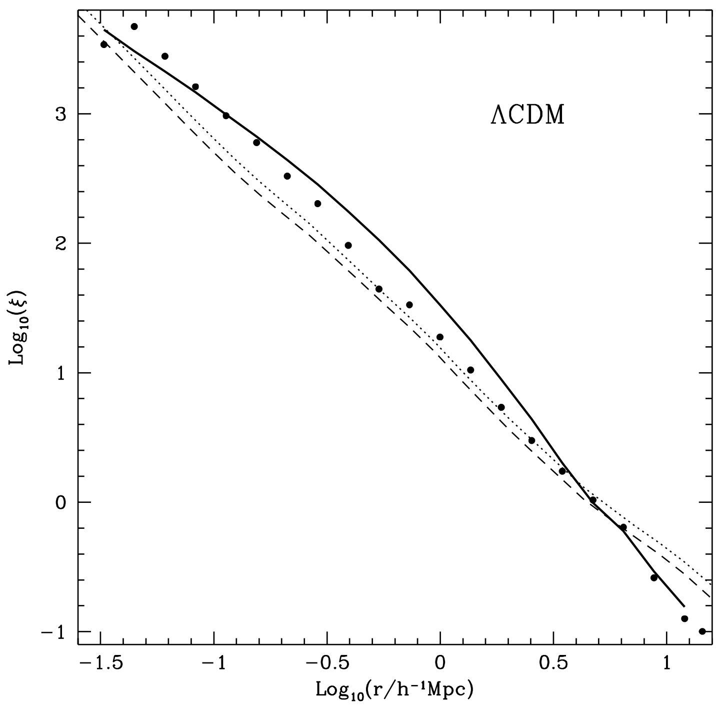

Figure 1: The two-point correlation function of the "galaxies" for the LCDM model (filled circles), compared to the mass correlation function (solid line) and the observed galaxy real-space correlation function (dashed/dotted - derived with different assumptions of clustering evolution[1])

For our simulations we rely on an effect of numerical resolution to mimic these feedback processes. The finite mass resolution in the simulation suppresses cooling in low mass halos and delays the onset of the formation of the cold dense gas phase (defined at $T < 10^4K$, and 60 000 times the mean gas density) which we identify as galaxies. We do not include star formation in the simulation, but assume that all the cold dense gas in the simulations should really be in the form of stars. The resolution is determined by the gas particle mass. We selected a gas particle mass such that the amount of gas in the cold dense phase at $z = 0$ in the SCDM model provides a reasonable match to the observed stellar mass density in the local universe.

With this choice of gas particle mass, which equates to $2 \times 10^9 M_{sun}$, we are able to simulate a 100 Mpc cubed shaped region with 128^3 particles of both gas and dark matter. This volume is large enough to study clustering statistics on scales up to 10 Mpc with a sample of about 2000 galaxies.

The simulations are started from a redshift of 50. The models we have simulated are a ΛCDM model with $\Omega_0 = 0.3$, $\Lambda_0 = 0.7$, $\sigma_8 = 0.9$, $h = 0.7$, $\Omega_b = 0.03$ and an SCDM model with $\Omega = 1$, $\sigma_8 = 0.6$, $h = 0.5$, $\Omega_b = 0.06$. The power spectra are the same as used for the models in [2] except that we used a higher value of σ_8 for SCDM.

2 The clustering of galaxies

The galaxies in the simulation are identified using a friends-of-friends group finder. The object catalog returned by the group finder is relatively insensitive to the linking length. We chose a linking-length of 1/50 of the mean *physical* interparticle separation at $z = 0$.

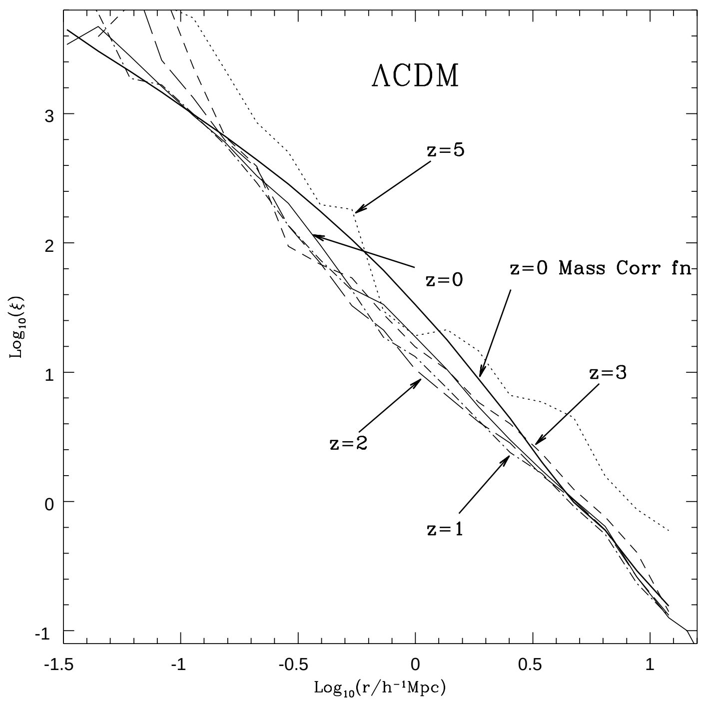

Figure 2: Evolution of the galaxy correlation function from redshift 5 to the present for the ΛCDM model. The bold line shows the $z = 0$ mass correlation function.

Figure 1 shows the two-point correlation functions for the simulated galaxies (filled circles), and dark matter (solid line) in the ΛCDM model. The observed galaxy correlation function [1] is shown as dashed and dotted lines. The latter is from [1]. On large scales the galaxies and mass have essentially the same correlation function. But on scales around $1Mpc/h$ the galaxy distribution is anti-biased with respect to the mass. The match to the observed galaxy correlation function is pretty good - in particular the simulated galaxy correlation function is close to a power law unlike the mass correlation function. A power law galaxy correlation function is also seen in the SCDM simulation.

Figure 2 shows the two-point correlation function of the galaxies in the ΛCDM model at a range of epochs. The amplitude of the correlation function has changed remarkably little from the present back until redshift of 3 even though the mass correlation function evolves linearly by a factor 10. At redshift 5 the galaxy clustering strength is significantly greater than at the present.

Figure 3 shows the line-of-sight pairwise velocity dispersion (explained in [2]) of the galaxies in the ΛCDM model compared to the dark matter, and a determination from the LCRS redshift survey [3]. The galaxies have a smaller dispersion than the dark matter, something which is clearly necessary for the viability of this cosmological model. We have found that if one selects the nearest dark matter particle to each galaxy, then the pairwise dispersion of these particles is essentially the same as the galaxies.

3 Summary

The clustering of the galaxies in the ΛCDM simulation is surprisingly close to the observed galaxy correlation function. Significantly in both ΛCDM and SCDM runs the galaxy correlation

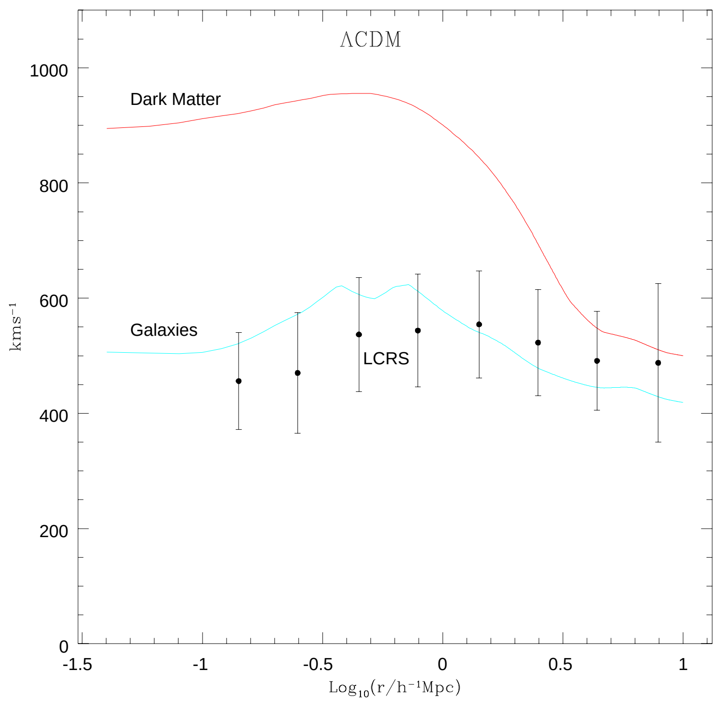

Figure 3: Pairwise velocity dispersion for dark matter and galaxies. The quantity plotted is the line-of-sight projection of the radial and transverse pairwise velocities (see [2] for details). Notice the significant difference between the measured dispersion of the galaxies and dark matter.

function is much closer to a power law than the mass correlation function. There is little evolution in the galaxy correlation function between redshift 3 and the present. For the ΛCDM model the pairwise galaxy velocity dispersion is much lower than that of the dark matter. A similar effect is seen in the pairwise dispersions of galaxies in the SCDM model, but weaker.

Acknowledgements. The simulations described here were run at the Edinburgh Parallel Computing Centre by the Virgo Consortium. CSF acknowledges a PPARC Senior Fellowship.

References

[1] Baugh C. M., 1996, *MNRAS* **280**, 267

[2] Jenkins A. et al, 1998, *Astrophys. J.* **499**, 20

[3] Jing, Y. P., Mo, H. J. & Börner, G., 1998, *Astrophys. J.* **494**, 1

[4] White. S. D. M. & Frenk, C. S., 1991, *Astrophys. J.* **379**, 25

[5] White, S. D. M. & Rees, M., 1978,*MNRAS* **183**, 341